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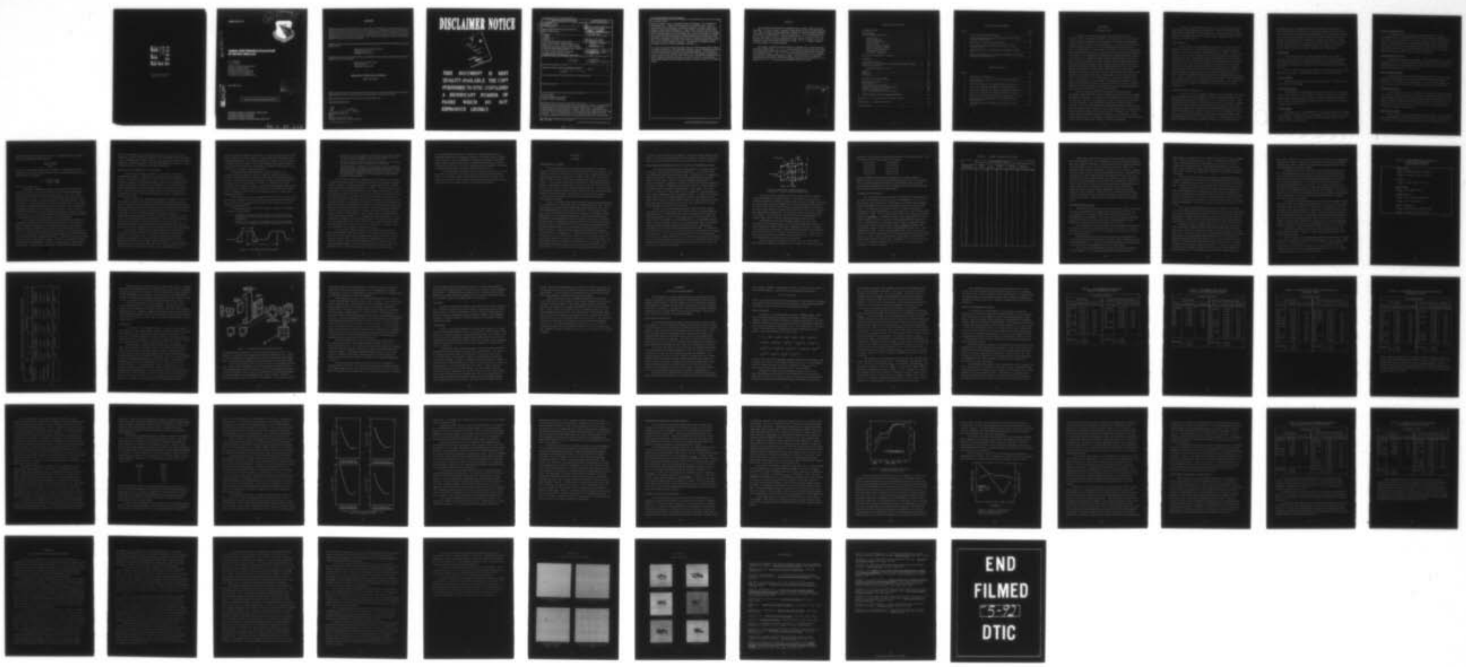

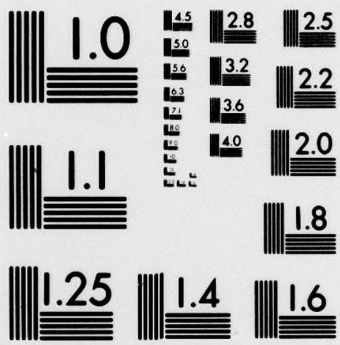

AMRL-TR-78-110

HUMAN PERFORMANCE EVALUATION OF MATRIX DISPLAYS

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

CHARLES BATES, JR.
Chief
Human Engineering Division
Aerospace Medical Research Laboratory

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The purpose of this research program was to investigate the influence of matrix display design parameters on operator target recognition performance. Five quantitative matrix display variables (emitter size, on-time, refresh-rate, viewing distance and emitter luminance) and two qualitative variables (emitter shape and packing format) were examined. The five quantitative factors were administered according to a Central-Composite, Response Surface Methodology experimental design to four subject groups

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20. Abstract (Cont'd)

defined by different emitter shape-packing format combinations. The shape-format combinations were: 1) square emitter packed in an orthogonal matrix, 2) square emitters packed non-orthogonally, 3) hexagonal emitters in a rhombic matrix, and 4) triangular emitters packed orthogonally. Target imagery consisted of profile photographs of tactical vehicles in uniform backgrounds. The observers' task was to recognize the moving targets, and the performance measure was target height at recognition. This measure was transformed into two dependent variables for data analysis, target subtended visual angle at recognition and the number of emitters on the target at recognition. These variables were used to fit a second-order linear polynomial equation by the method of stepwise multiple regression. This equation was designed to specify performance in terms of the five quantitative variables.

The results showed that shape and packing format do not differentially influence target recognition performance. Of the quantitative variables, only viewing distance accounted for a large proportion of the variance in the regression equation. Viewing distance could be recast into the subtended visual angle of the emitter spacing for optimal performance and this value was 0.42 mrad (1.46 arc min). Because the contribution of the other variables to operator performance was small, the results are interpreted as meaning that designers have wide latitude with these variables to achieve a cost-effective design.

PREFACE

The research covered herein was initiated by the Aerospace Medical Research Laboratory, Air Force Systems Command, United States Air Force, Wright-Patterson AFB, Ohio, to conduct a human engineering evaluation of advanced display technology. The contract was initiated under Air Force Project 7184. The Technical Monitor for the Air Force was Mr. Wayne L. Martin (6570 AMRL/HEA). The research was conducted by the Display Systems Department of Hughes Aircraft Company, Culver City, California, under USAF contract F33615-76-C-0503. Dr. L. A. Scanlan of Hughes Aircraft Company was Program Manager.

The authors would like to thank a number of colleagues who rendered invaluable assistance to this project. Mr. D. W. Craig provided much help with the target imagery and prepared the final set of negatives. The analysis of matrix display variables was suggested by Ms. A. Agin. Mr. C. Dickson was instrumental in the early phases of this project, including the equipment design. Much useful advice on statistical analyses and the intricacies of the BMD computer programs was provided by Mr. D. C. Fulkerson. Ms. L. A. Olzak aided in statistical analysis of the data.

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SECTION 1

INTRODUCTION

A display is the critical transducer converting information in electronic form to information useful to a human operator. It goes without saying that aircraft displays have undergone rapid changes paralleling the changes in other aspects of aircraft technology. The increasing complexity of modern high performance aircraft demands displays that can convey a variety of information, a requirement in contrast to a meter or gauge which typically monitors the status of a single parameter of the internal or external environment. The introduction of cockpit radar brought with it the cathode-ray-tube (CRT) as a display medium and this ubiquitous device has proved to be an adequate substrate for quite complex display configurations such as the heads-up display (HUD), vertical situation display (VSD), and the horizontal situation display (HSD). Such configurations often require the simultaneous presentation of information in both symbolic and sensor form. Symbolic information is typically conveyed using symbols like alphanumerics or pointers and graphs while sensor information is derived from sensors such as radar, FLIR, or TV which provide a visual representation of the external environment. As an example, a VSD might be configured so that flight control information such as airspeed, altitude, and course heading, is displayed graphically around the periphery of a sensor display showing the forward terrain in the form of, say, a FLIR image.

The CRT, while adequate to the demands of complex display technology, suffers from the hardware limitations of excessive size, weight, and power consumption. In response to the evolutionary pressure to make aircraft more efficient by reducing size, weight, and power requirements of all aircraft systems, a new generation of flat-panel, matrix displays is evolving. Such devices include light emitting diodes (LEDs), liquid crystal (LX), and plasma panel displays. All are characterized by a two dimensional array or matrix of discrete elements that either emit light (e.g., LEDs or plasma panels) or differentially reflect light (e.g., LX displays). These matrix displays (MDs) are attractive alternatives to CRTs as display mediums in view of their modest size, weight, and power consumption.

MDs have, of course, seen wide use in a number of applications as displays of strictly alphanumeric information. These uses would include such common applications as the readout on hand-held calculators or digital watches. The display of sensor or visual image information, however, is the concern of this report.

THE PROBLEM

At this point in the development of sensor MDs, it is not clear what design trade-offs may be made while optimizing, or at least preserving, adequate information transfer to the human operator. Indeed, a more basic question is what design parameters exert the most influence on human performance with MDs. It would not require a human factors research effort to realize that a MD composed of very small emitters packed very densely could reproduce images with high fidelity and presumably with excellent operator performance. Such a display design, however, is unrealistic in view of hardware considerations. Thus, the requirement is to determine to what degree the design of a MD may be shifted or degraded from the above hypothetical optimum without seriously compromising human performance. This is another way of saying that design variables of the display must be specified in terms of the performance of the operator. This research is a first step in this direction, focusing on the display of sensor or image information.

MATRIX DISPLAY VARIABLES

The use of CRTs as a display medium has been thoroughly investigated and the parameters of these displays that influence human performance are well known and will not be treated here (e.g., see Biberman, 1973). When considering matrix displays, a likely first step would be to identify analogous variables, between CRTs and matrix displays; one might then expect that, based on the extant CRT literature, the variables that influence performance with CRTs would operate in a similar manner with matrix displays. This, however, may not be a productive strategy because matrix displays differ fundamentally from CRTs in a number of ways. For example, the distribution of luminance on a CRT is spatially continuous in one dimension and

discontinuous in the orthogonal dimension, while MDs by nature have a discrete distribution of luminance in both spatial dimensions. Scanlan and Carel (1976) have reviewed much of the literature concerning matrix displays and they conclude that proper consideration of MDs requires that the parameters of these displays be considered as a unique set. Since any display operates in both the temporal and spatial domains, these rubrics are a convenient starting point when considering display parameters. Scanlan and Carel identify and define the spatial variables of a MD as follows

Emitter Size.

The physical extent of the light emitting surface. For square emitters, size is given by the edge dimensions; for circular, the diameter. For emitters without a square luminance profile, that is emitters with an edge luminance gradient (see below) the 50 percent luminance point defines the size.

Size may also be expressed in terms of visual angle, θ, if the viewing distance, d, is known. Visual angle is given by: $\theta = 2 \arctan (h/2d)$.

Emitter Spacing.

The distance between centers of adjacent emitters. Spacing may also be described in visual angle.

Percent Active Area.

The amount of the total display surface that emits light. For square emitters, percent active area is given by: (Emitter size/Emitter spacing)^2 x 100; for other shapes, the total active area must be computed on the basis of the emitter size and number of emitters and this result divided by the total available display surface area.

Emitter Shape.

The emitters in an MD potentially can be any geometric shape. Shape is an important variable because it will influence how the emitters are packed on the display. In addition, shape impacts the maximum possible percent active area for a given display.

Emitter Packing Format.

A classification of the geometry of the emitters in the matrix. Orthogonal packing is defined when the centers of emitters in adjacent rows and columns are in register. To an extent, emitter shape dictates packing format. For example, circular emitters would pack "best", in the sense that the percent active area is maximized (see Legault (1973) for a brief discussion of this point) in a rhombic matrix, with the centers of adjacent emitters forming the vertices of an equalateral triangle.

Edge Luminance Gradient.

The luminance profile of the emitter. Typically emitters have a sharp luminance edge (or a square luminance profile); alternatively, the luminance distribution may taper off gradually. The latter instance is similar to the gaussian luminance profile of a CRT spot.

Other Spatial Variables.

Scanlan and Carel discuss three additional spatial variables, symbol definition, symbol subtense, and font, for matrix displays transmitting symbolic (i.e., alphanumeric) information. Because symbolic displays are not the subject of this report, these variables will not be discussed here.

Temporal Variables.

A matrix display also has variables in the temporal domain. Present and projected matrix displays do not emit light continuously, but rather emit pulses at some frequency. The duration of these pulses specifies the on time and the frequency of the pulses gives the refresh rate of the display. The ratio of the on time to the period, where the period is the reciprocal of the refresh rate, defines the duty cycle.

Luminance Variables.

Finally, there are luminance parameters important to matrix displays. The emitter luminance specifies the output of a given emitter on the display. The inactive area luminance (obviously, germane only to displays with less

than 100 percent active area) may also vary. Together, these variables define the maximum possible contrast

$$\frac{L_{max} - L_{min}}{L_{min}}$$

which will vary between minus and plus infinity. Alternatively, the two luminance values may be expressed in terms of maximum possible modulation using the relationship,

$$M = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

which ranges from 0 to 1.

In addition to defining the unique variables of MDs, Scanlan and Carel also provide a review of the behavioral literature investigating the influence of these variables on human performance. Two major points emerge from this effort. First, nearly all experimental studies of MD's have focused on displays conveying symbolic, chiefly alphanumeric, rather than sensor or image information. As such, the bulk of this matrix display literature is of limited usefulness to the present effort. The concentration on symbolic displays has come about for two reasons. First, symbolic displays have been the major use of matrix displays to the present. Second, it is relatively easy to simulate symbolic matrix displays with the flexibility of parameters necessary for human factors experimentation.

The only study identified that dealt with sensor matrix displays was conducted by Martin, Task, Woodruff and Pinkus (1976). Percent active area and emitter spacing were the variables of interest in this study; the latter variable was manipulated by changing the viewing distance of the observer. Martin, et al. simulated a sensor display by placing a grid mask over a rear-projection screen on which target imagery was zoomed up from a very small size until recognition occurred. Percent active area was varied from 55 percent to 100 percent, but this variable had no statistically significant influence on performance. Emitter spacing, however, did influence performance. Larger emitter spacing was associated with larger target

sizes at recognition, for spacings larger than 0.43 mrad (1.5 arc min.); below this value the acuity of the observer was the limiting factor and target size at recognition was roughly constant. This result agreed with the author's prediction. The Martin, et al. study notwithstanding, the influence of sensor display variables on performance is largely unexplored.

SELECTION OF INDEPENDENT VARIABLES

Given the set of display parameters, all of which are potential independent variables, a problem arises concerning which variables to select. Prima facie it would be desirable to select all, or some subset, of the above variables as experimental factors; however, this situation cannot obtain because these variables are not independent. For example, for a given shape, emitter size and spacing combine to determine percent active area. Obviously, two of these variables cannot be held constant and the third uniquely varied. Such interdependencies preclude a straightforward selection of variables.

What is required is a rationale for selecting independent variables. One approach would be to attempt to identify influential design parameters from previous research, but this approach was not adopted for two reasons. First, the Scanlan and Carel review made it clear that most of their potential independent variables have been largely ignored. Other studies, moreover, are of little value in predicting important parameters because of confoundings among independent variables. Second, as pointed out above, nearly all MD experiments dealt with symbolic rather than sensor displays. The type of information conveyed by symbolic and sensor displays is sufficiently different to question the utility of making predictions about performance with sensor displays based on data obtained from symbolic displays.

An alternative rationale for selecting independent variables is to recast the design parameters into variables of potential relevance to the operation of the visual system. A number of models of visual spatio-temporal processing (e.g., Rashbass, 1970, 1976; Schnitzler 1976a, b; Watson and Nachmias, 1977; Legge, 1978) posit that the visual system is composed of a series of filters operating in the spatial or temporal domains. Visual stimuli are inputs to these filters and are described in terms of

spatial or temporal luminance waveforms. The same approach may be used when considering a matrix display as a visual stimulus, independent of the information displayed. The rows and columns of emitters may be treated as a periodic spatial waveform. That matrix displays emit pulses of light at some refresh rate means that the temporal properties of the display may be described by a periodic temporal waveform.

A generalized periodic waveform is shown in Figure 1. By considering this waveform in either the spatial or temporal domains, a number of analogies between variables in the temporal and spatial domains emerge. In the spatial domain, dimension "A" corresponds to emitter size, as defined above; for a temporal waveform, "A" simply is the on time. Dimension "B", spatially, corresponds to emitter spacing while temporarily it is the period of the waveform; the reciprocal of the period is the refresh rate. Dimension C and C' refer to rise and decay times or spatial edge luminance gradients.

This analysis also reveals analogies between derived variables. The duty cycle of a display is the ratio of the on-time to the period (A/B), while the percent active area is given by the square of the ratio of emitter size to emitter spacing ($(A/B)^2$).

The foregoing analysis provides a basis for selecting the following variables in the experiment:

1. Emitter size - This variable is the major determinant of the spatial characteristics of the display and as such is of obvious importance.
2. On time - This variable is included because it is the analogue, in the temporal domain, of the spatial variable emitter size.

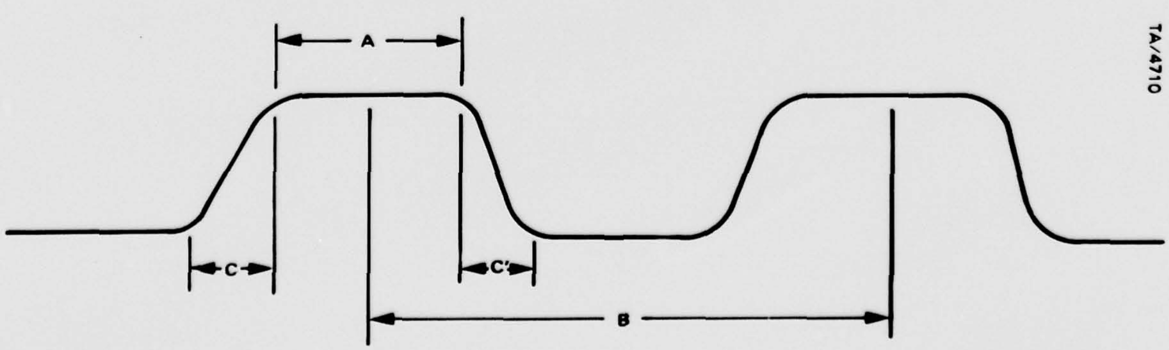


Figure 1. Generalized periodic waveform

3. Refresh rate - This variable, combined with the on-time, defines the duty cycle of the display. Duty cycle is important because it is the temporal analogue of percent active area.

4. Emitter luminance - This variable was included since all spatial and temporal waveforms are functions of luminance.

5. Viewing distance - Included as a convenient way of manipulating emitter spacing. Changing viewing distance changes the visual angle of the emitter spacing; this allows the spacing to be manipulated without changing the number of emitters across a target of a given size, as would occur if spacing was changed with a constant viewing distance.

Emitter shape and emitter packing format are unique matrix display variables that might influence performance and were also included as experimental variables. In distinction to the five variables listed above, emitter shape and packing format are qualitative variables. Various shapes or packing formats are easily differentiable from one another, but there is no common attribute or metric that can easily express the degree of difference. On the other hand, the five variables above are all quantitative, because they are easily measured in units that express the magnitude of differences. The distinction between a quantitative and qualitative variable has importance for the Response Surface Methodology experimental design employed in this study which is restricted to quantitative variables. Accommodating the qualitative variables into the design requires a separate group for each combination of emitter shape and packing format. Thus emitter shape and packing format are between-group variables, i.e., changing only between groups. The five quantitative variables were varied within groups. The result is that a subject in a given group observed a matrix display with a particular emitter shape and packing format; emitter size, on-time, refresh rate, luminance, and viewing distance were varied according to the design.

The question now focuses on which of the emitter shape-packing format combinations ought to be selected. The criterion used in this study was that all shape-packing format combinations could, in the limit, reach 100 percent active area. Thus the following combinations were selected: 1) square emitters, packed in an orthogonal matrix; 2) square emitters in a non-orthogonal matrix, where non-orthogonal means that the centers of adjacent rows of emitters are offset by one-half of the normal emitter

spacing and alternate rows are in register; 3) triangular emitters in an orthogonal matrix; and 4) hexagonal emitters in a rhombic matrix, similar to a honeycomb. These combinations contrast with a display constructed from circular emitters where there is no packing format that can achieve 100 percent active area. Likewise, hexagonal emitters packed in an orthogonal format are limited to less than 100 percent active area.

The experiment examined the effects of the five quantitative variables and the four combinations of emitter shape and packing format identified above on an operator's ability to recognize tactical vehicle targets. The targets were moved across a uniform background during experimental trails, with target size at recognition taken as the dependent variable.

SECTION 2

METHOD

EXPERIMENTAL DESIGN

The goal of this study was to specify the functional relationship between operator performance and design variables of matrix displays. The variables selected for this study were emitter shape and packing format as between-group factors, and emitter size (ES), on-time (OT), refresh rate (RR), emitter luminance (EL), and viewing distance (VD) as within-group factors. For any group viewing a particular emitter shape-packing format display, performance is specified as a function of ES, OT, RR, EL and VD. The true form of the function, called the response surface, which describes the relationship between operator performance and the five variables selected is unknown and would require each subject in a full factorial design to receive 3,125 experimental trials for a full replication, obviously an impossibly large number.

However, techniques have been developed which permit approximation of a response sufrace while collecting a reasonable amount of data. The so-called Response Surface Methodology (RSM), orginally developed to aid in maximizing industrial processes (Box and Hunter, 1957; Box and Wilson, 1951), has been adapted to behavioral research (Clark and Williges, 1972). RSM designs realize significant economies in data collection through the simplifying assumption that interactions beyond the second-order typically do not account for a significant proportion of the total experimental variance. In other words, such higher-order interactions do not materially influence the experimental result, are not important predictors of performance, and thus need not be accounted for in the polynominal equation describing the response surface. In particular, a Central-Composite Design (CCD), as one of the general class of RSM designs, achieves data collection economy by collecting enough data to generate a second-order regression equation. For the present study only 27 experimental conditions were required. These 27 observations allowed an equation to be derived which included the linear main effect of each variable, all linear-by-linear interactions between

variables, and the quadratic main effects. Clark and Williges (1972) provide tables and rules for determining the required number of experimental conditions for central-composite RSM designs with different numbers of factors.

GEOMETRIC REPRESENTATION OF A CENTRAL-COMPOSITE DESIGN.

In a central-composite design the data points are carefully selected to sample a large portion of the experimental space, so as to extract the most information from the fewest data points. This design is a composite of a standard factorial design and a set of points distributed symmetrically about a "center point." The 27 treatment conditions in this study were selected such that 16 conditions represent a one-half replicate of a standard 2^5 factorial design, 10 conditions represent the "star" or "axial" portion of the design and the remaining condition is the "center point." The terms "star" or "axial" and "center point" refer to a geometric representation of the treatment conditions of the experimental design. A complete 5^5 factorial design has 3,125 experimental conditions, which if represented geometrically, would result in a 5-dimensional "hyper-cube" with 5 points along each dimension where the dimensions refer to the experimental factors and the points along them refer to the factor levels.

Because a five-dimensional hypercube is difficult both to imagine and diagram, Figure 2 presents a three-factor central composite design in diagramatic form. In the three factor case, the design is a composite of a 2^3 factorial (filled circles), a center point, and star or axial points. The edges of the cube in Figure 2 represent the factors, and the points along the edges represent the factor levels. As in any geometric figure, the location of all the points in Figure 2 could be specified by a three dimensional coordinate in terms of the units of the factors of the design. To extend the generality of such designs, it is useful to specify the coordinates of the points in coded values. Thus, the points representing the 2^3 factorial portion of the design are assigned coded values of ± 1, the center point has the coordinate (0, 0, 0) and the star points have values of $\pm \alpha$. The real-world values corresponding to these coded values depends on the range of values of a factor the experimenter wishes to investigate.

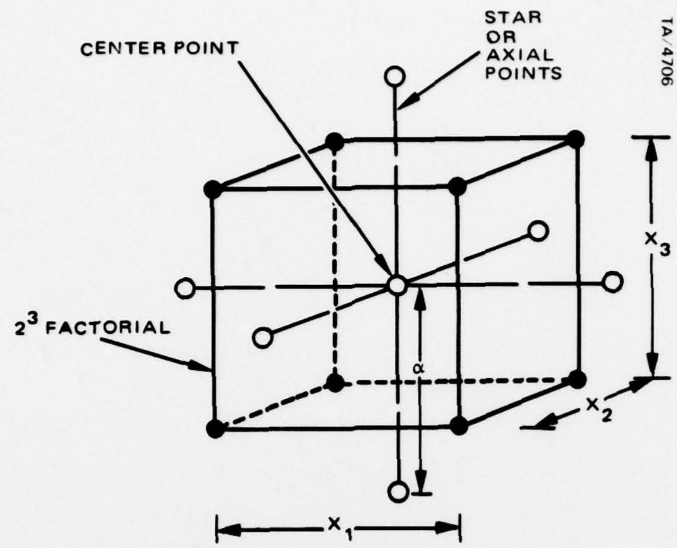


Figure 2. Geometric representation of a three-factor central-composite RSM design.

The experimental conditions in the five-factor CCD are assigned coded coordinates in a similar manner. Each point in the "hypercube" could be specified by a 5-digit coordinate and, because each point represents an experimental treatment condition, the 5-digit coordinate would specify the level of each factor in that particular treatment condition. The point at the center of the hypercube has the coordinates (0, 0, 0, 0, 0,) and represents the experimental condition where the mid-range value of all factor levels is presented. As an example, refresh rate is to be investigated over the range of 10 to 110 Hz, then the center point of this range is 60 Hz.

Recall that 16 of the experimental conditions refer to a half-replicate of a 2^5 factorial design. A 2^5 factorial samples the 5 factors at two levels giving a total of 32 possible combinations, but only 16 of these are used in the present design. In terms of our geometrical conceptualization, these two levels are assigned coordinate values of ±1. Since the 16 points in this portion of the design all have coordinates of +1 and -1, they are symmetrically arrayed about the center point.

The final points to be explained are the "star" or "axial" points. These points are assigned coordinates of $\pm\alpha$, where α is a coded value that

depends on other design considerations which will be considered below. The coordinates of the 10 star points are as follows:

$(\alpha, 0, 0, 0, 0)$	$(-\alpha, 0, 0, 0, 0)$
$(0, \alpha, 0, 0, 0)$	$(0, -\alpha, 0, 0, 0)$
$(0, 0, \alpha, 0, 0)$	$(0, 0, -\alpha, 0, 0)$
$(0, 0, 0, \alpha, 0)$	$(0, 0, 0, -\alpha, 0)$
$(0, 0, 0, 0, \alpha)$	$(0, 0, 0, 0, -\alpha)$

These coordinates show that the star points are arranged radially at distances of $\pm\alpha$ from the center point; hence the terms star or axial points. These coordinates indicate that the star points of the design represent experimental conditions where the $\pm\alpha$ level of one factor is associated with the mid-range value of all the other factors.

CODED FACTOR LEVELS

The result of these considerations is that the five levels that each of the experimental factors assume are some combination of $\pm\alpha$, ± 1, and 0. To reiterate, these numbers are coded values, used only in discussing the design and <u>do not</u> represent real-world values of any of the experimental factors. To complete the design, the value of α must be determined. Depending on design considerations, α may range from 1.414 to 2.828 (Clark and Williges, 1972). For the present experiment, α was selected so that the design was <u>rotatable</u>. A rotatable design has the property that the variance of the predicted response is equal at all data points equidistant from the center. Rotatability is a useful property for designs in exploratory work, such as this experiment, where there is little <u>a priori</u> knowledge of the shape of the response surface and its orientation to the factor axes. For a rotatable five-factor central-composite RSM design, α has a value of 2.0. Therefore, the full set of coded values of the factor levels in this experiment was ± 2, ± 1, and 0. Table 1 presents the coded values for each of the 27 experimental conditions of this study. Conditions 1 to 16 are the half replicate of a 2^5 factorial, conditions 17 to 26 are the ten star points, and condition 27 is the center point.

TABLE 1. CODED VALUES OF FACTORS

Experimental Condition	Experimental Factors				
	Emitter Size	On Time	Refresh Rate	Viewing Distance	Emitter Luminance
1	-1	-1	1	-1	-1
2	-1	-1	-1	-1	1
3	1	-1	-1	-1	-1
4	1	-1	1	-1	1
5	-1	1	-1	-1	-1
6	-1	1	1	-1	1
7	1	1	1	-1	-1
8	1	1	-1	-1	1
9	-1	-1	-1	1	-1
10	-1	-1	1	1	1
11	1	-1	1	1	-1
12	1	-1	-1	1	1
13	-1	1	1	1	-1
14	-1	1	-1	1	1
15	1	1	-1	1	-1
16	1	1	1	1	1
17	0	0	0	0	-2
18	0	0	0	0	2
19	-2	0	0	0	0
20	2	0	0	0	0
21	0	-2	0	0	0
22	0	2	0	0	0
23	0	0	0	-2	0
24	0	0	0	2	0
25	0	0	-2	0	0
26	0	0	2	0	0
27	0	0	0	0	0

This design was taken from Cochran and Cox (1957) as modified by Mills and Williges (1973). The modification concerned the number of times the center point was replicated. Cochran and Cox (1957) suggest replicating the center point 6 times to use the variance of the center point as an estimate of the variance of the entire response surface. However, Williges and Barron (1973) provide data demonstrating that variance estimated by the variance of the center point may not be adequate for behavorial research. Specifically, variance estimated only from replication of the center point was large and consequently no main effects were statistically reliable. If, however, the entire design was replicated and variance estimated over the entire surface, the error variance was smaller and previously non-significant effects were found to be significant. Thus, the replicated design was more sensitive. Williges and Barron (1973) point out that in a replicated design it is unnecessary to present the center point more than once per replication. This procedure was followed in the present experiments.

Real-World Factor Levels

With the design specified in terms of coded factor levels, it was then necessary to establish the corresponding real-world factor levels. To accomplish this, the range of values over which each factor was to be investigated had to be defined. The coded value 0 corresponds to the mid-point of the range of each factor, therefore, having defined the range, finding the real-world value of the coded value 0 is trivial.

The α points were also easy to find. By definition the coded values of $\pm\alpha$ always represent the end points on the range of any factor. In the present design $\pm\alpha$ correspond to ± 2, so the extreme values were also set once the range was defined.

The final points were the real-world values corresponding to ± 1. If 0 is defined as the mid-range value of a factor, and the end points are the $\pm\alpha$ values (in this case $\alpha = 2$), then the linear transform needed to find the real-world values corresponding to ± 1 may be easily found.

The ranges of the independent variables were selected as follows. Because emitter size, emitter spacing, and percent active area are

interrelated, the second two were constrained to define the range of emitter size. That is, emitter spacing was set at a constant value of 0.0635 cm (.025 in) (40 emitters/inch) or 200 emitters across the 12.7 cm (5 in) display used in the experiment. With emitter spacing fixed, the percent active area was held to a maximum of 90 percent and a minimum of 20 percent. Thus, emitter size ranged from 0.0284 cm (0.0112 in) to 0.0602 cm (0.0237 in).

The range of the refresh rate variable was selected both to span a range from well below to well above the critical flicker fusion frequency and to have a midpoint at or near 60 Hz, which is the refresh rate of a CRT display. A range of refresh rates from 10 to 110 Hz satisfied these criteria.

With the range of the refresh rate of the display determined, the on-time of the display had to be constrained so that, for any combination of refresh rate and on-time, the on-time did not exceed the period determined by the reciprocal of the refresh rate. This constraint had to be imposed because an on-time greater than the refresh rate period results in a display that is on continually. Under this constraint, the on-time range was 0.5 to 15 ms.

The range of viewing distance was set to a minimum of 30.48 cm (12 in.) to avoid problems with accommodation and to insure viewing comfort. A maximum viewing distance of 182.88 cm (72 in.) was selected so that the visual angle subtended by the emitter spacing was near the acuity limit of the observer. At the maximum viewing distance the visual angle subtended by the 0.0635 cm (0.025 in.) emitter spacing is 0.34 mrad (1.19 arc min).

Setting the range of emitter luminance presents a special problem. This experiment employed displays with various combinations of on-time and refresh-rate which means that the duty cycle of the display is variable (duty cycle = on-time x refresh rate). Experimenting with displays incorporating temporally modulated light with different duty cycles introduces an important potential confounding, that of the time average luminance of the display. According to the Talbot-Plateau law (Graham, 1965), a constant luminance source that is temporally modulated, for example, on a 90 percent duty cycle will appear brighter than the same source modulated on a 20 percent duty cycle. The time-average luminance is higher for higher

duty cycles. Therefore, in an experiment where luminance is an independent variable, the brightness differences introduced by the temporal modulation of the display must be controlled to insure that the luminance factor is not confounded with the temporal variables.

Luminance control was achieved by first calculating the duty-cycle for each combination of on-time and refresh rate used in the experiment. Then all duty cycles were normalized to the lowest duty cycle and the log of this ratio was taken to determine the attenuation of the display required to achieve equal brightness. For example, the lowest duty cycle was 3 percent and the highest was 96.9 percent. The ratio yields a total of 1.51 log units of attenuation necessary to equate the brightness of the 96.9 percent duty cycle condition to the 3 percent duty cycle condition. These calculations were checked by measuring the time average luminance of the display using a photometer. The measured values diverged from the calculated values by at most 0.04 log units.

In addition to the attenuation necessary to equate the luminance of the display for differences induced by temporal factors, the range of the emitter luminance factor was varied over 1.5 log units. A logarithmic scale was selected because the visual system responds in an essentially linear manner to changes in log intensity (Graham, 1965). Because luminance changes in the experimental apparatus were effected by inserting neutral density filters, the real world values of the luminance factor were expressed as log attenuation. Thus the range of this factor extended from -1.5 log to 0 log attenuation. The maximum luminance on the display was 205.58 cd/m^2 (60 fL), therefore luminance ranged from 205.58 cd/m^2 (60 fL) to 6.51 (1.9 fL).

Table 2 gives the linear transform used to convert coded to real-world values for the five variables. Table 3 lists the actual factor values used in the experiment.

Table 3 may be used in conjunction with Table 1 to find the real-world values of all variables for any experimental condition. For example, condition #1 (i.e., coded values of -1, -1, 1, -1, -1) is a display where the emitter size was 0.0338 cm (0.0133 in.), the on-time was 4.1 ms, the refresh rate was 85 Hz, the viewing distance was 68.58 cm (27 in.) and the emitter luminance was 56.29 cd/m^2 (16.43 fL).

TABLE 2. TRANSFORMATIONS REQUIRED TO CONVERT CODED TO REAL-WORLD VALUES

Emitter Size:

$$ES_{RW} = (0.00794 \times ES_c) + 0.0444 \text{ cm.}$$

$$ES_{RW} = (0.003125 \times ES_c) + 0.0175 \text{ in.}$$

On Time:

$$OT_{RW} = (3.625 \times OT_c) + 7.75 \text{ ms}$$

Refresh Rate:

$$RR_{RW} = (25 \times RR_c) + 60 \text{ Hz}$$

Viewing Distance:

$$VD_{RW} = (38.1 \times VD_c) + 106.68 \text{ cm}$$

$$VD_{RW} = (15 \times VD_c) + 42 \text{ in.}$$

Emitter Luminance:

$$EL_{RW} = (49.78 \times EL_c) + 106.06 \text{ cd/m}^2$$

$$EL_{RW} = (14.525 \times EL_c) + 30.95 \text{ fL}$$

TABLE 3. REAL-WORLD VALUES CORRESPONDING TO CODED VALUES

Variables	Coded Values				
	-2	-1	-0	1	2
Emitter Size	0.00305 cm 0.0012 in.	0.0338 cm 0.0133 in.	0.0444 cm 0.0175 in.	0.0523 cm 0.0206 in.	0.0602 cm 0.0237 in.
On-Time	0.5 ms	4.1 ms	7.8 ms	11.4 ms	15.0 ms
Refresh Rate	10 Hz	35 Hz	60 Hz	85 Hz	110 Hz
Viewing Distance	30.48 cm 12 in.	68.58 cm 27 in.	106.68 cm 42 in.	144.78 cm 57 in.	182.88 cm 72 in.
Emitter Luminance	6.51 cd/m^2 1.9 fL	56.29 cd/m^2 16.43 fL	106.04 cd/m^2 30.95 fL	155.83 cd/m^2 45.48 fL	205.58 cd/m^2 60 fL

Subjects did not receive trials in the order listed in Table 1. Rather, the trials were distributed so that, within any group, the trials representing the factorial portion of the design, the star portion and the center point were equally distributed across sessions. This was to insure that differential practice or fatigue effects would not systematically bias the results as might occur if all subjects received trials only in the order shown in Table 1.

A final design feature must be mentioned. On any given trial a subject viewed one of a set of six target images. Since there were six targets and 27 conditions each subject saw three targets five times and three targets four times. However, within any group the target presentations were counterbalanced so that all targets were presented an equal number of times and so that each target was paired with each experimental condition an equal number of times.

APPARATUS

The apparatus, schematized in Figure 3, provided a photo-optical simulation of a sensor matrix display which permitted the display parameters to be varied over the ranges dictated by the experimental design. The apparatus essentially consisted of a system in which moving imagery could be projected with provisions for a mask that simulated the matrix of emitters and a rotating shutter to impart temporal properties to the display.

The light source of the projection system was a 120V, 500W lamp (G. E. CBA) excited by a DC power supply, to eliminate the 60 Hz flicker caused by driving the lamp with the AC line voltage. Preliminary work revealed that at refresh rates that ought to be well above fusion frequency, the interaction of the 60 Hz AC flicker with flicker due to the rotating shutter caused unacceptable visible luminous beat frequencies. The light beam passed through an infra-red reflecting mirror to reduce the infra-red content of the beam, a condensing lens system, past the 12. 7 cm (5 in.) film gate and the matrix element mask, and was brought to focus at the location of the rotating shutter. A projection lens enlarged the image of the film and the matrix mask by a factor of 1. 7 before it was rear projected on a 12. 7 cm x 12. 7 cm (5 in. x 5 in.) ground glass screen in front of the observer. Intensity was controlled by neutral density filters (Kodak

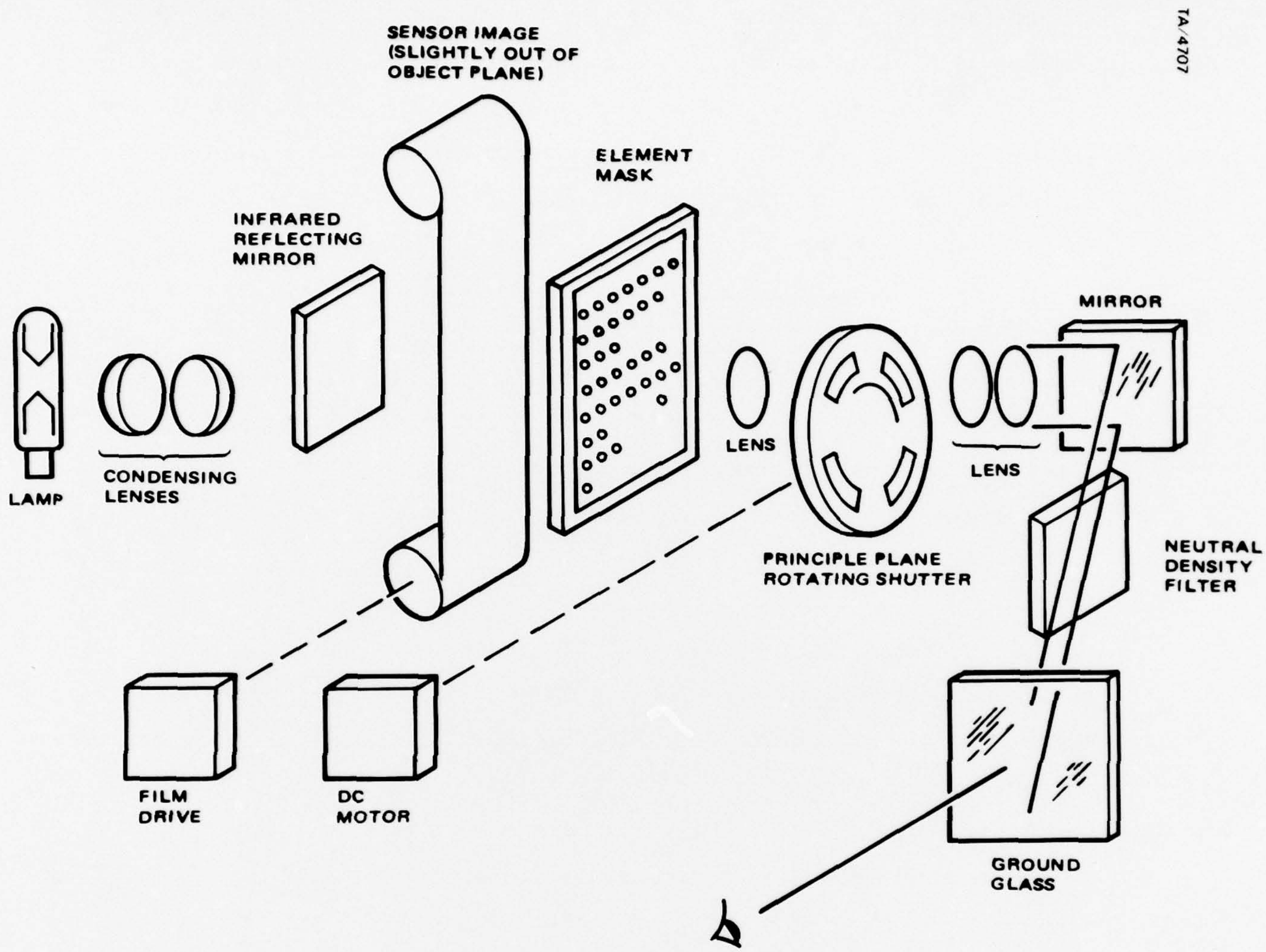


Figure 3. Schematic of experimental apparatus.

Wratten #96) placed between the projection lens and display screen. The filters were calibrated with a photometer (Gamma Model 2000) and a regulated 100 FL light source (Photo Research Spectra), both instruments having been recently calibrated against reference standards traceable to the NBS.

The matrix element masks were the key to the matrix display simulation. These masks essentially were a film transparency with open areas corresponding to the emitters and opaque areas corresponding to the inactive area of the display. These masks were fabricated by the Automated Design Facility of Hughes Aircraft Company using a Gerber plotter, capable of accuracies on the order of a 0.00127 cm (0.0005 in.). The mask was placed

in the object plane of the projection lens so that the image of the element mask was in sharp focus on the display screen. Photographs, enlarged five times for clarity, of representative masks used in the four emitter shape-packing format groups are shown in Appendix A.

The target imagery was a set of profile photographs of H. O. scale models of the following tactical vehicles: tank, tow truck, crane, APC, 5-ton truck, and half-track. These images were on a continuous 12. 7 cm (5 in.) film transparency that was moved across the film aperture behind the matrix mask. The observer saw the images move smoothly across the display from left to right at about 1. 19 cm/s (0. 47 in/s). The images were spaced on the film strip so that only one image appeared on the display screen at a time. Because the dependent measure was the image size at recognition, each image was prepared in 10 sizes: 0. 28 cm (0. 11 in), 0. 46 cm (0. 18 in), 0. 64 cm (0. 25 in), 0. 81 cm (0. 32 in), 0. 91 cm (0. 36 in), 1. 04 cm (0. 41 in), 1. 22 cm (0. 48 in), 1. 40 cm (0. 55 in), 1. 52 cm (0. 60 in), 1. 75 cm (0. 69 in). Preparing the different images in equivalent sizes controlled for recognition based on size cues alone. The images were ordered on the film so that the 10 different sizes of a single target appeared in order of increasing size. Appendix B shows photographs of each target type.

The film strip was not in the same plane of focus as the matrix element mask but rather was positioned behind the plane of focus (i. e., toward the light source). As a result, the images of the targets were slightly out of focus, thereby greatly reducing the luminous modulation within the simulated emitters. Reducing modulation within emitters is necessary to achieve a realistic matrix display simulation because a basic feature of matrix displays is that no luminance modulation can exist within individual elements.

The temporal characteristics of the display were controlled by rotating shutters driven by a DC motor (Electro-Craft Corp. #0650-00-004). The rotating shutters were sectored discs fabricated from 2 mil brass shim stock and rotated in the principal plane of the final projection lens. Openings

cut in the shutter allowed one display refresh with on-time determined by the width of the openings and the refresh rate was set by the speed of rotation of the shutter. Calibration of the rotation speed was achieved with a strobe light (General Radio Strobolume #1540) driven by a function generator (Wavetek 145) whose output was monitored with an oscilloscope.

SUBJECTS

Twenty-four Hughes Aircraft Co. personnel, 14 males and 10 females, were randomly assigned to one of four groups. Each group viewed a matrix display that was a unique combination of emitter shape and packing format: 1) square emitters, orthogonal packing; 2) square emitters, non-orthogonal packing; 3) hexagonal emitters, rhombic packing; or 4) triangular emitters, orthogonal packing.

PROCEDURE

The 27 experimental conditions were given to the subjects in a single session lasting approximately one hour. On any given trial the subject viewed images of a single target type in steps of increasing size. The subjects' task was to correctly recognize the target being presented and the target size at recognition was the dependent variable. Size at recognition was operationally defined as the target size at the first correct response in a sequence of two correct responses.

A trial began with the display blanked. The experimenter unblanked the display and the subject saw a target, at the smallest size, move across the display from left to right. It required 10.6 s for the image to move across the display and the subjects could use all of this time to study the image before making a response. Subjects could respond either by stating which target type they felt they saw or with no response if they were unsure of the target type. As was most often the case, when a response was made before the image had traversed the display, the experimenter manually advanced the film transport to the next size image to conserve time. Following a sequence of two similar responses, the trial was terminated by the experimenter blanking the display and setting up the combination of factor levels appropriate for the next trial, a procedure which required about a

minute. Because viewing distance was a factor, the subject was asked, at the appropriate times, to move his/her chair to the point designated by the experimenter. A chin and head rest attached to the chair insured that the five viewing distances would be the same for all subjects.

Prior to the start of data collection all subjects were tested for acuity with a Snellen chart and given instructions outlining the purpose and procedure of the experiment. The models photographed for the target imagery were shown to the subjects to familiarize them with the six target types. These models were labeled and were available for the subject to view throughout the experiment. The experimenter further told the subject that if a target was recognized but its name was not recalled, the subject could refer to the labeled model to obtain the correct name. This procedure was to assure that target recognition was not confounded by forgetting a target name. The instructions given the subject also made clear that a response should be made only when the subject was very sure of the target type and that no feedback would be given as to the correctness of the subjects' responses.

SECTION 3

RESULTS AND DISCUSSION

The performance measure obtained during the experiment, target height at recognition, was transformed into two dependent variables for the purpose of data analysis. These variables were the visual angle subtended by the target at recognition and the number of emitters across the height of the target at recognition. The data were analyzed by the method of stepwise regression to fit a second-order linear polynomial equation. These steps will be discussed in detail in the sections to follow.

DEPENDENT VARIABLES

The principal dependent variable in this study was the target height at recognition, where recognition is defined as the first of a sequence of two correct responses. The target height variable was expressed in cm, but the absolute size of the target is not of primary interest in this study. Therefore, the target height at recognition was recast into two variables, one relevant to MD system design and the other more directly related to the performance of the human operator. The former variable was the target height expressed as the number of emitters that fall across the height of the target and the latter variable was the visual angle subtended by the target.

The number of emitters across the target was computed by dividing the target height by the emitter spacing of 0.0635 cm (0.025 in) which was constant at this value for all experimental groups and conditions. The smallest target size, 0.28 cm (0.11 in) had 4.4 emitters across its height. Now this raises a question as to how to deal with a fractional number of emitters across the target. Because in a real matrix display there could not be a fractional number of emitters across a target, the number of emitters was rounded to the nearest integer value. In the above example, the 4.4 emitters would be rounded to 4 for purposes of data analysis.

The visual angle subtended by the target was calculated on the basis of the rounded number of emitters. In the above example, the rounded value

of 4 emitters resulted in a height of 4 x 0.0635 = 0.254 cm where 0.0635 cm is the emitter spacing. Visual angle was computed by the formula:

$$\theta = 2 \text{ arc tan } h/2D$$

where h is target height and D is viewing distance. Calculating the subtended visual angle in this way insured that this measure and the computed number of emitters across the target were of comparable precision.

DATA ANALYSIS

A stepwise regression computer program, BMD02R (Dixon, 1973) was the primary analysis technique used to obtain multiple regression equations relating the display variables to operator performance. The independent variables were transgenerated to a form that allowed development of a regression equation containing 21 terms: one constant term, fine linear terms, 10 linear-by-linear interactions, and five quadratic (2nd order terms). The model equation is thus of the form:

$$\begin{aligned}\hat{y} = {} & \beta_0 + \beta_1 ES + \beta_2 OT + \beta_3 RR + \beta_4 VD + \beta_5 EL + \beta_6 ES \cdot OT \\ & + \beta_7 ES \cdot RR + \beta_8 ES \cdot VD + \beta_9 ES \cdot EL + \beta_{10} OT \cdot RR + \beta_{11} OT \cdot VD \\ & + \beta_{12} OT \cdot EL + \beta_{13} RR \cdot VD + \beta_{14} RR \cdot EL + \beta_{15} VD \cdot EL + \beta_{16} ES^2 \\ & + \beta_{17} OT^2 + \beta_{19} RR^2 + \beta_{20} VD^2 + \beta_{21} EL^2 + \epsilon\end{aligned}$$

where $\hat{y}$ is the value of the dependent variable predicted by the equation, ES is emitter size, OT is on time, RR is refresh rate, VD is viewing distance and EL is emitter luminance, β_0 is the constant term, β_{1-21} are the regression coefficients for the terms, and ϵ is an error term.

Although the model regression equation contains 21 terms the reported equations typically do not. This situation arises because of the nature of the stepwise regression technique. Stepwise regression proceeds by initially calculating the correlations among all variables and selecting

the independent variable most strongly correlated with the dependent variable. If this independent variable is, say, x_1, then a linear regression equation of the form $\hat{y} = \beta_0 + \beta_1 x_1$ is calculated. Then from the set of variables not in the equation the independent variable with the highest partial correlation coefficient to $\hat{y}$ is then selected and entered into the equation. At each step the program also tests previously entered terms to determine if they should remain in the equation or should be removed because of new relationships among the variables in the equation.

Statistically the procedure outlined above is equivalent to entering first the variable maximally reducing the error or residual sum-of-squares (SS_{Res}). The selection and entry of variables continues until either all variables have been incorporated into the equation or until the variables can no longer satisfy a predetermined numerical criterion. A more complete discussion of stepwise regression techniques may be found in Draper and Smith, (1966). However, the regression equation given by the final step of the program is not necessarily, from either a statistical or practical standpoint, the best equation to report as a final result. This is because the program will include terms that produce very small reductions in SS_{Res}. At each step the SS_{Res} is divided by the residual degrees-of-freedom (df_{Res}) to obtain the residual mean square (MS_{Res}) and the square root of this value is equal to the standard error of the estimate of the dependent variable. If at some step in the regression program a term is entered which makes a very small reduction in SS_{Res}, dividing by df_{Res} may result in an increase in MS_{Res}, which is the same as saying the standard error of the estimate increases.

For example, in the analysis of one group's data the standard error of the estimate on step six was 7.0201. The program entered another term on the next step and the resulting SS_{Res} was 7600.285. Dividing SS_{Res} by its degrees of freedom, 154, gave $MS_{Res} = 49.352$ and the square root of this or the standard error of the estimate = 7.0251. Taking an increase in the standard error of the estimate as a stopping criterion, only the terms entered through step in this example six would be included in this report. That is, the regression equations include only those terms whose inclusion effected an overall decrease in the standard error of the estimate.

This stopping criterion does not materially influence the results because the terms deleted typically would by themselves or in combination account for very small percentages of the overall variance. In other words, the deleted terms are not strong predictors of the dependent variable and including or deleting them from a prediction equation makes little practical difference.

GROUP REGRESSION EQUATIONS

The initial step in data analysis was to generate a regression equation for each of the two dependent variables and for each of the groups where groups are the four different emitter shape/packing format combinations: square-orthogonal (SO), square-non-orthogonal (SN), hexagonal-rhombic (HR) and triangular-orthogonal (TO). The initial analysis was done with the independent variables in their RSM coded form, i.e., ± 2, ± 1, and 0. When the independent variables are coded in this way the absolute value of the regression coefficients give an indication of the relative importance of each term in predicting performance. The regression equations for the two dependent variables and four groups are presented in Tables 4 through 7. The equations are presented in tabular form to facilitate comparisons within and across groups.

Note first that these equations all contain far fewer than the 21 terms specified by the model equation presented above. This result simply means that of the terms that potentially may enter the equation, not all are good predictors of target recognition performance. In other words, the terms that do not enter the equation are not important aspects of the display from the standpoint of the human operator as assessed by the performance measure used in this experiment.

Examination of the equations shows that expressing the dependent variable, target height at recognition, in two different ways - subtended visual angle and number of emitters across the target - did not produce regression equations with equal predictive power. Specifically, visual angle always produced equations accounting for more variance by a factor of about two, than equations based on the number of emitters across the target height.

TABLE 4. REGRESSION EQUATION FOR SQUARE-ORTHOGONAL GROUP

Dependent Variable					
Visual Angle			Number of Emitters on Target		
Term	Coefficient	% Variance	Term	Coefficient	% Variance
Constant	16.690	-	Constant	8.2716	-
VD	-6.4677	36.32	VD x EL	-0.6875	3.31
VD^2	2.5705	6.38	VD	0.6528	4.48
VD x EL	-1.4627	1.24	OT	0.5000	2.63
OT	1.3895	1.68	ES	-0.4861	2.48
OT x VD	-1.1794	0.81	OT x RR	0.4379	1.34
RR x VD	-1.0400	0.63	EL	-0.4028	1.71
ES	-0.9632	0.81	RR x VD	-0.3542	0.88
OT x RR	0.8517	0.42			
RR	0.6740	0.34			
Multiple R = 0.6976 R^2 = 0.4866			Multiple R = 0.4102 R^2 = 0.1682		

TABLE 5. REGRESSION EQUATION FOR SQUARE-NON-ORTHOGONAL GROUP

Dependent Variable					
Visual Angle			Number of Emitters on Target		
Term	Coefficient	% Variance	Term	Coefficient	% Variance
Constant	17.0122	-	Constant	8.4907	-
VD	-5.6941	33.48	VD	1.1111	11.65
VD^2	2.6721	8.28	EL	-0.5417	2.77
RR	1.1449	1.35	RR	0.5139	2.49
EL	-1.0702	1.18	ES x EL	0.3958	0.99
OT^2	-0.6106	0.61	ES x VD	-0.3542	0.79
EL^2	0.5406	0.30	OT x RR	0.3542	0.79
			EL^2	0.3212	1.43
			VD x EL	-0.2917	0.54
			ES	0.2917	0.80
			OT^2	0.2413	0.59
Multiple R = 0.6745 R^2 = 0.4549			Multiple R = 0.4778 R^2 = 0.2005		

TABLE 6. REGRESSION EQUATION FOR HEXAGONAL-RHOMBIC GROUP

Dependent Variable					
Visual Angle			Number of Emitters on Target		
Term	Coefficient	% Variance	Term	Coefficient	% Variance
Constant	16.7351	-	Constant	8.4445	-
VD	-8.1366	37.14	OT x RR	0.7917	3.18
VD^2	4.1292	9.70	OT x VD	-0.6042	1.85
OT x RR	1.9147	1.37	RR x VD	-0.5417	1.49
OT x VD	-1.9105	1.37	ES x OT	-0.5208	1.38
RR x VD	-1.8164	1.23	VD	0.5139	2.01
ES x OT	-1.4957	0.84	OT^2	0.5000	1.68
RR	1.4415	1.17	RR	0.4722	1.70
OT	1.0662	0.64	EL	-0.3889	1.15
RR x EL	1.0241	0.39	VD x EL	-0.3333	0.56
ES x EL	-1.0030	0.38	OT	0.2778	0.59
OT^2	0.9216	0.51	VD^2	0.2708	0.60
Multiple R = 0.7398 R^2 = 0.5473			Multiple R = 0.4025 R^2 = 0.1620		

TABLE 7. REGRESSION EQUATION FOR TRIANGULAR ORTHOGONAL GROUP

Dependent Variable					
Visual Angle			Number of Emitters on Target		
Term	Coefficient	% Variance	Term	Coefficient	% Variance
Constant	17.7257	-	Constant	8.7778	-
VD	-6.0474	36.11	VD	0.8750	8.36
VD^2	2.4740	6.72	OT x RR	0.6667	3.24
EL	-1.7148	2.90	EL	-0.5837	3.72
OT x RR	1.5989	1.68	OT x EL	0.5417	2.14
VD x EL	1.5599	1.60	ES	-0.4861	2.58
RR	1.1567	1.32	RR	0.4583	2.30
ES	-1.0556	1.10	OT	0.3750	1.54
RR x VD	-0.9174	0.55	VD x EL	0.2708	0.53
OT x VD	-0.8620	0.49	OT x VD	-0.2708	0.53
OT	0.8231	0.67	RR x VD	-0.1458	0.15
OT x EL	0.8170	0.44	EL^2	0.1250	0.19
Multiple R = 0.7320 R^2 = 0.5358			Multiple R = 0.5028 R^2 = 0.2528		

This is shown by comparing the coefficients of determination, which are the square of the multiple regression coefficients, and are measures of the proportion of the total variance the regression equation explains. Across groups the average coefficient of determination is 0.5062 for equations using the visual angle dependent variable, while the same value for the number of emitters measure is 0.1959.

The result that the visual angle dependent variable is a better performance predictor than the number of emitters across the target relates to the so-called 'Johnson criteria.' In 1958 Johnson empirically derived criteria that expressed target detection and recognition in terms of the number of television line pairs that fall across the target. The present results show that an analogous measure for matrix displays, i.e., the number of emitters across the target, is not as good a performance predictor as the visual angle of the target. This result is explicable if one considers what aspects of a target must be maximized for recognition. For any target to be recognized it must have sufficient contrast, it must be large enough, and the target must have a sufficient number of resolution elements across it. In the present experiment the visual angle dependent variable took into consideration of two of these properties, size and number of resolution elements, while the other dependent variable, the number of emitters across the target, considers only one. Therefore it is not surprising that the visual angle dependent variable accounts for more experimental variance and hence is a better performance predictor.

Examination of Tables 4 to 7 allows a determination of the terms exerting the greatest influence on performance. Consideration of the equation expressing performance as the visual angle of the target at recognition, reveals that the two most important terms of the equation, those terms with the largest regression coefficient or those accounting for the most variance, are the linear and quadratic viewing distance (VD) terms. The linear VD term always enters the regression equation first, and explains the largest portion of the variance. This term accounts for an average, across groups, of 35.76 percent of the total experimental variance which is an average of 62 percent of the variance that is accounted for by the entire regression equation. Clearly, when considering the visual angle of the targets at recognition, viewing distance is an important performance predictor.

In any regression equation the sign of the regression coefficient of a term is indicative of the nature of the relationship between the independent variable and the dependent variable. Note that in the four equations employing the visual angle dependent variable the VD term always has a negative

coefficient. This may be interpreted as a negative correlation between the visual angle of the target at recognition and viewing distance. Stated another way, the negative correlation means that large VD values tend to be associated with small visual angle measures, which is interpreted as good performance, and small VD values go with large values of visual angle or poor performance.

The negative correlation between VD and the visual angle subtended by the target at recognition is at first glance counter intuitive - one would expect that, as the observer is moved further away from the display, the target would have to be larger for recognition to occur. However, if one assumes that target height at recognition is constant at all viewing distances, then a strong negative correlation results between VD and target visual angle at recognition. A brief example will illustrate this point. Assume that the target height at recognition was constant at 0.15"; then the relation between viewing distance, and these are the values used in this experiment, and visual angle is.

Viewing Distance	Visual Angle
12"	42.97'
27"	19.09'
42"	12.27'
57"	9.04'
72"	7.16'

The Pearson product-moment correlation coefficient for these values is -0.88. For the actual data over all groups the correlation between VD and visual angle is -0.59. While this comparison is hardly conclusive, it does lend support to the notion that the explanation of the negative regression coefficients of the VD terms might be that target recognition occurs at approximately constant target heights.

However, the interpretation of these data is not as straightforward as the above discussion might imply. The second term to enter these equations - again, only the equations based on the visual angle dependent variable are

under present consideration - is the quadratic or VD^2 term. The presence of such a term in a regression equation means that the relation between visual angle at recognition and viewing distance is not well described by a straight line, but that the relation has curvature. This implies the existence of a minimum point on the function relating visual angle at recognition to viewing distance. Thus, the quadratic term means that if viewing distance is increased beyond this minimum point, performance will deteriorate.

Figure 4 plots the regression equation specifying target visual angle as a function of viewing distance. The plots were derived by plotting the regression equation with only the VD and VD^2 terms and thus the equations were of the general form $y = C + \beta_1 VD + \beta_2 VD^2$, where C is the constant term, β_1 and β_2 are the coefficients of the VD and VD^2 terms, respectively. All equations were plotted as functions of the coded viewing distance values.

Examination of the curves clearly shows that each has a minimum point and that this point is located in about the same position in all cases. The location of the minimum point may be interpreted as the viewing distance that yields optimum performance. Because the emitter spacing was constant at 0.0635 cm (0.025 in), knowing the optimal viewing distance permits calculation of the optimal subtense, in visual angle, of the emitter spacing. The subtense of the emitter spacing is needed to find the value, in centimeters or inches, of the emitter spacing for a display with a predetermined viewing distance. The minimum points in the curves of Figure 4 were calculated by finding the first derivative of the regression equation, setting it equal to zero, and solving for VD. This results in coded VD values which are transformed into real world values using the transformations listed in Table 2. The final step is to find the subtense of the emitter spacing at these optimal values.

Proceeding in this manner, the optimal viewing distance values are 154.6 cm (60.9 in.) for the S-O group, 147.1 cm (57.9 in.) for the S-N group, 144.2 cm (56.8 in.) for the H-R group, and 153.2 cm (60.4 in.) for the T-O group. These values translate into emitter spacing subtense values of 0.40 mrad (1.41 arc min), 0.42 mrad (1.48 arc min), 0.43 mrad (1.51 arc min), and 0.41 mrad (1.42 arc min) for the S-O, S-N, H-R, and T-O groups

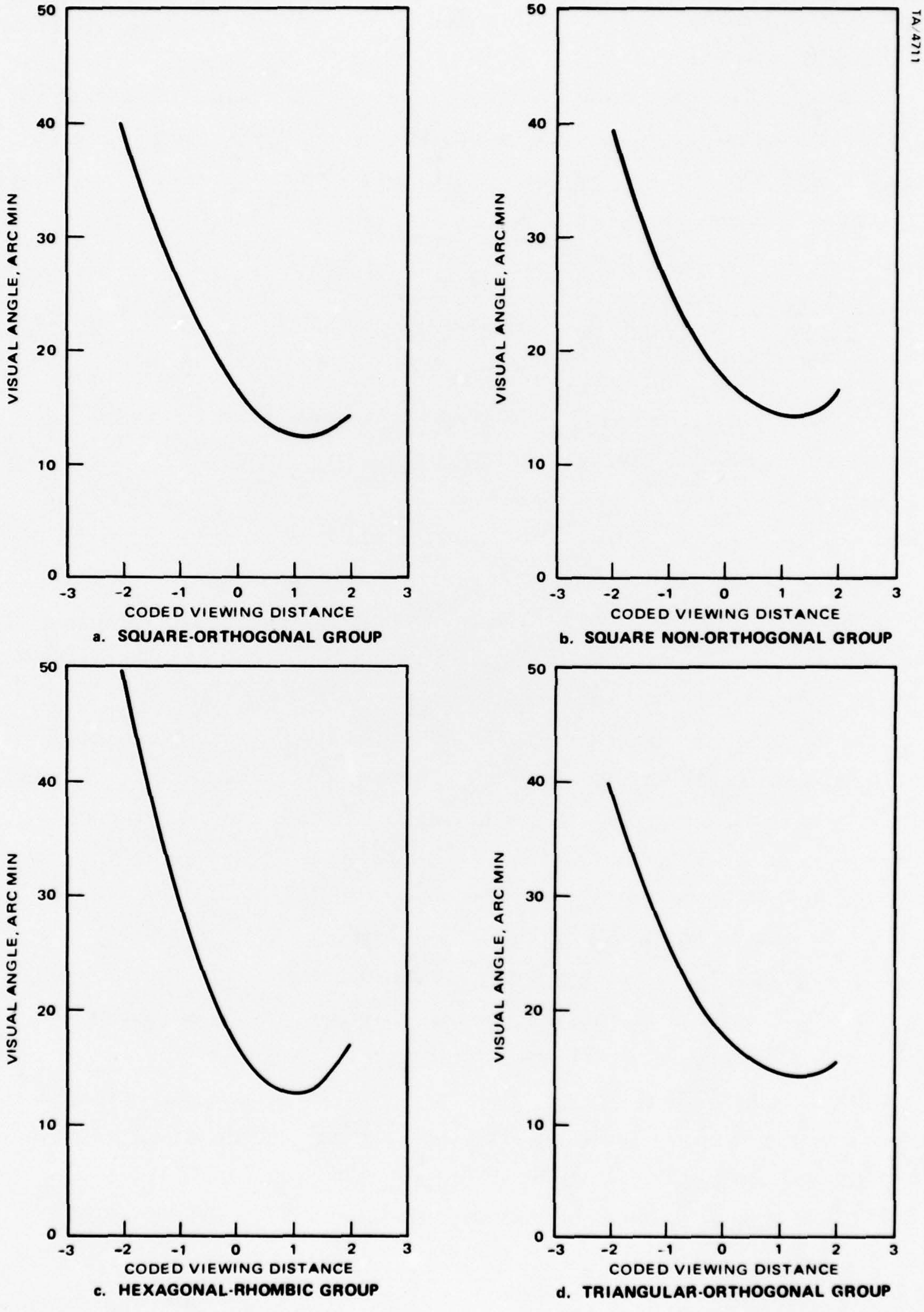


Figure 4. Plots of regression equation using only viewing distance terms.

respectively. Averaging these values gives 0.42 mrad (1.46 arc min) as the optimal emitter spacing.

It should be noted, however, that the optimal value of 1.46 mrad is, in an operational sense, a non-conservative figure. This is because this figure is based on an extended viewing time. With the present experimental apparatus, the target images were exposed to the subjects for up to 10 sec, while an operational situation might permit only a 3 to 5 sec exposure to the target before a pilot must decide whether the target is recognized.

Beyond the first two terms of the equations, the importance and interpretation of the terms become less clear, a situation which arises for two reasons. First, taken individually, these additional terms each account for only a small proportion, about 1 to 2 percent, of the total variance and as such their impact as performance predictors is small. Second, inspection of the terms of the equations across groups clearly shows that large differences exist between groups, when the terms that comprise these equations are considered. However, based on the present analysis it is not possible to demonstrate whether these are statistically significant group differences; this point will be addressed more fully below.

Nevertheless, some general statements may be made about other variables that influence performance. The refresh rate (RR) of the display enters into all of the equations, indicating it has some predictive power. However, it accounts for only a small amount of the total experimental variance, so this variable is probably not a strong performance predictor. The other temporal variable, on-time (OT), likewise appears in three equations, but again accounts for only small amounts of variance. Further, these equations show that emitter luminance (EL) and emitter size (ES) do not seem to influence performance in any strong way; stated another way, these equations show that EL and ES are not important design parameters.

The regression equations for the other dependent variable - the number of emitters across the target height - are, unfortunately, even more difficult to interpret. At the outset note that between all groups these

equations account for far less, about 20 percent, of the experimental variance than the other set of equations. In addition, each of the terms of these equations accounts for only a small portion of the total variance accounted for by the complete equation, which makes the task of assessing the role of these terms as performance predictors difficult. Note, however, that a commonality among these equations is that viewing distance or a viewing distance interaction is always among the most important terms. This result tends to confirm the importance of the VD and VD^2 terms in the other set of equations.

Further, the present set of equations confirms the result, based on the set of equations using visual angle as a dependent variable, that the range of temporal parameters of the display examined here play only a small role in predicting performance. The on-time (OT) and refresh rate (RR) terms each appear in three of the four regression equations accounting, however, for but a small proportion of the variance. The emitter size (ES) term, also makes only a small contribution to the prediction of performance in both sets of equations. It must be pointed out, however, that the final linear term, emitter luminance (EL), appears to exert more influence on performance in the present set of equations than in the set based on visual angle. An emitter luminance term appears in all four regression equations based on the number of emitters across the target, while the luminance term is found in only two equations based on the visual angle dependent variable. Furthermore, in the equations based on the number of emitters, the EL term accounts for a largei proportion of the variance accounted for by the equation, then in comparison to the equations based on visual angle. That is, the luminance term accounts for an average of 11.4 percent of the variance accounted for by the equations based on number of emitters, while the same term accounts for only about 4 percent of the variance in the equations based on visual angle.

ANALYSIS OF VARIANCE ON GROUP MEANS

The results presented above indicate that there are differences among the regression equations for the different groups in terms of the variables present in the equations as well as the proportion of variance accounted for by each variable. This raises the question whether the groups themselves differ. To answer this question a three-way, mixed-effects analysis of variance was performed on the data with groups as a fixed effect with four levels, subjects as a random effect with six levels, and the treatment conditions as a fixed effect with 27 levels.

For both dependent variables there were no reliable differences due to groups; that is, the emitter shape-packing format combinations the subjects viewed did not influence the results. For the visual angle dependent variable the groups factor was not significant, $F_{(3, 20)} = 0.7036$, a value which indicates failure to reject the hypothesis of differences between groups. For the dependent variable of number of emitters across the target height, the groups factor was also non-significant, $F_{(3, 20)} = 0.5917$. The treatments factor was highly significant for both dependent variables, however. For the visual angle dependent variable the treatments factor had an $F_{(26, 520)} = 3.8295$, ($\underline{p} < 0.01$) and for the number of emitters dependent variable, the treatments effect had an $F_{(26, 520)} = 5.4787$ ($\underline{p} < .01$). These results indicate that the hypothesis that no differences exist in the data due to the experimental factors may reliably be rejected. Thus, the five quantative independent variables did indeed influence target recognition performance, but no emitter shape-packing format combination was better or worse for target recognition than any other.

FURTHER ANALYSIS OF VARIANCE

The results presented in the previous section show that there is a significant treatment effect; that is, some aspect of the different treatment conditions. Two aspects of the treatments, the target type and a learning effect over the session, could contribute to the significant treatment effect. To analyze the data for these effects a three-way mixed effect analysis of variance was performed, investigating target type (six levels, fixed effect), replications (five levels, fixed effect) and subjects (24 levels, random effect).

It should be noted that in the experiment proper there were 27 trials and six target types. Thus, each subject saw three targets five times and the other three targets four times. To analyze the data based on six targets and five replications of each target type, "dummy" data had to be added to the target types replicated only four times so that there would be an equal number of target types per replication, in accord with the limitation of the analysis of variance program BMD08V (Dixon, 1973) used here. These dummy data were simply zeros and were always added to the fifth replication. Because dummy data were added for all six target types there should be no differential effect of the dummy data on a particular target type and thus, the overall impact of this operation is minimal. In fact, inserting zeros as dummy data tends to make any subsequent test more conservative; that is, there is less chance of showing a statistically significant result when in fact there is one. This conservatism is preferred over the other rational way of inserting dummy data which would be to insert the means of data obtained from similar target types, which leads to less conservative tests.

The analysis indicated a significant target type effect. In other words, the target types were not equally easy to recognize. For the visual angle and number of emitters dependent variables, the F-ratios were, respectively $F_{(5, 115)} = 4.3305$ ($\underline{p} < 0.01$) and $F_{(5, 115)} = 8.4528$ ($\underline{p} < 0.01$). Thus the hypothesis of no difference in ease of recognition among targets may reliably be rejected. Figure 5 presents the mean number of emitters across the target at recognition (left ordinate, solid circles) and mean target subtense, in mrad, at recognition (right ordinate, open circles) plotted against target type. The pattern appears similar in both cases: the 5-ton truck was easiest to recognize, the tank and tow truck were more difficult but about equal, and the half-track, crane, and APC were most difficult, but about equally so.

These differences were tested by the Newman-Keuls critical range test (Keppel, 1973) which is a technique for pairwise comparisons of means to isolate the significant effect previously demonstrated by a significant main effect.

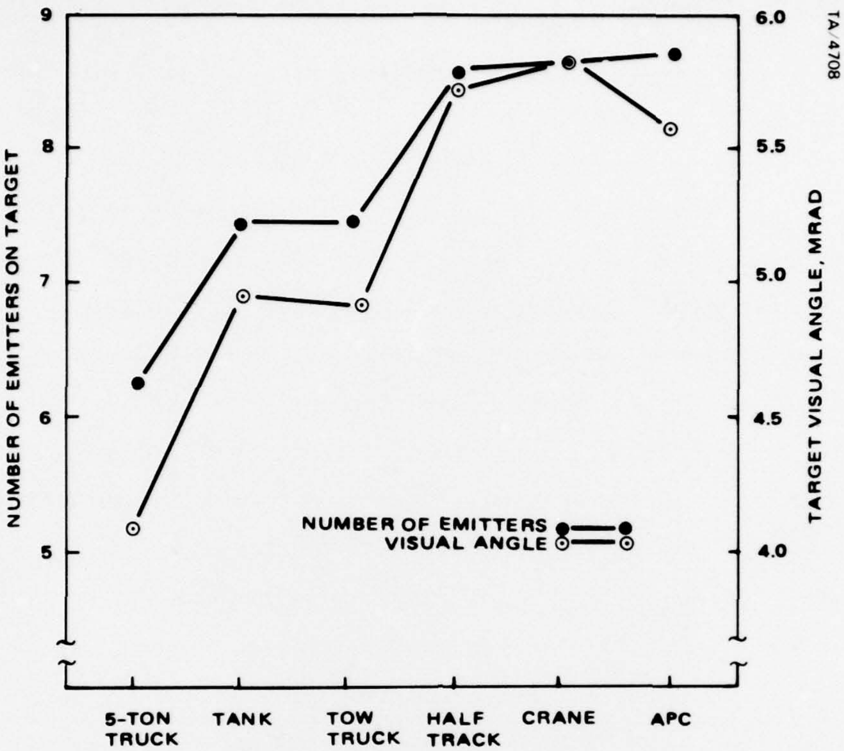


Figure 5. Target recognition performance for different target types.

For the most part the differences in means apparent in Figure 5 are verified by the results of the Newman-Keuls tests. Considering first the number of emitters data (Figure 5, left ordinate, solid circles), the tests show significant differences between the 5-ton truck target and all remaining targets, significant differences between the tank and half-track, and significant differences between the tow truck and the half-track and the crane. No other comparisons were significant. Here all tests were considered significant if $\underline{p} < 0.05$. These results confirm the expectations based on simple inspection of the data. No difference was found between the tank and tow truck and no differences were found between the half-track, crane, and APC. One would expect significant differences between the tank and the crane and APC since the tank-half track comparison was significant. The tank-half track and tank-APC comparisons approached significance; the fact these comparisons were not significant relates to an adjustment for the number of means spanned. The significant tank-half-track comparison spanned three

means, while the tank-crane and tank-APC spanned five and six means, respectively. The latter two comparisons are more distant, hence the test is more stringent. A similar argument can be made to account for the result showing significant tow truck-half track and tow truck-crane comparisons, but not a significant tow truck-crane comparison.

The results of the tests on the data for the other dependent variable, target subtense at recognition, show that the only significant comparison is between the 5-ton truck and the APC, half-track, and crane. The 5-ton truck-tank and 5-ton truck-tow truck comparisons approached significance and probably did not achieve significance because of the inherent conservatism of the test, as discussed above.

Figure 6 shows the results of a test to determine if performance improved over a session. Here a replication is defined as the mean performance score over each block of six target presentations; again, the fifth

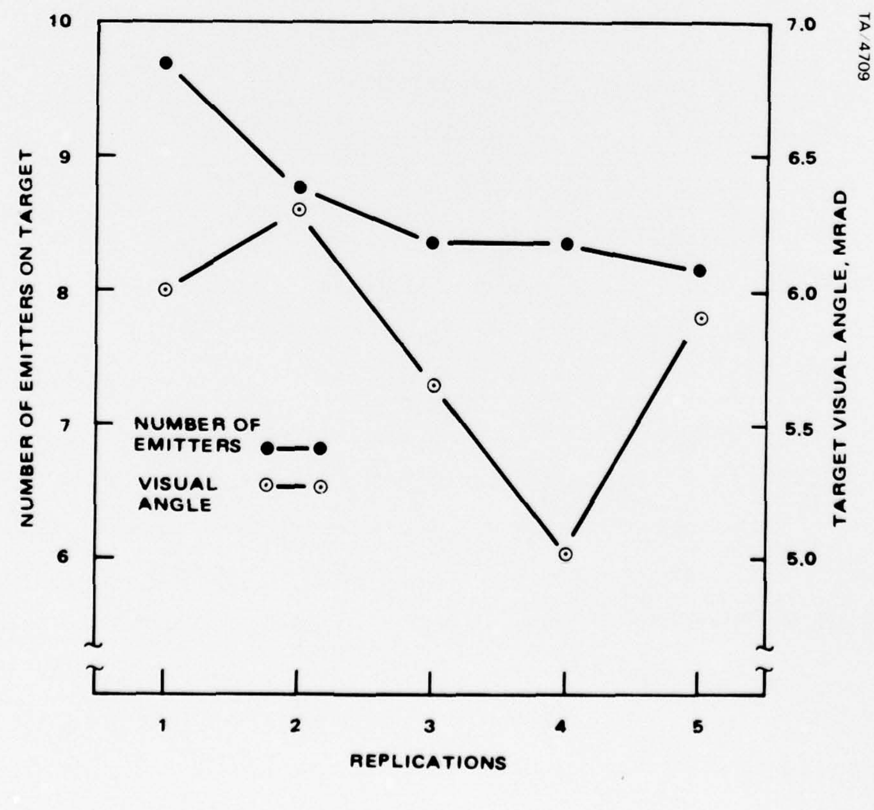


Figure 6. Effect of replications on target recognition performance showing a learning effect.

replication had to be adjusted for missing data as outlined above. That both curves generally show performance improving over replications may be atrributed to a "learning" effect during the session, i.e., the subjects got better at the recognition task as they became more familiar with the targets. The results of the Newman-Keuls tests support this conclusion. The data for the number of emitters dependent variable show that the first replication is significantly different from all other replications and was the only significant difference. Results for the other dependent variable, target subtense, show only that replication 4 is significantly different from both replications 2 and 5. However, the reason for the superior performance on replication 4 as assessed by the target subtense measure is unclear, and is most likely a statistical fluctuation.

These results, taken together, are important in revealing sources of error variance in this experiment. The group regression equations presented above account for, at most, about 50 percent of the total experimental variance. The remaining variance must be attributed to the catch-all of "experimental error". Demonstrating that targets are not equally recognizable and that subjects' performance improves somewhat during a session identifies two sources of this "experimental error". The implication is that had these factors been carefully controlled, the predictive power of the regression equations would be improved and this improvement would be revealed by an increase in the variance accounted for by the regression equation.

Results such as these, however, are not uncommon. Martin, et al. (1975), which is the study most germane to the present experiment, also found differences in the difficulty of recognition among the targets they used, as well as substantial learning effects up through approximately 40 presentations of each of five tactical target types. These problems are inherent in any study employing realistic targets. Even though the targets in the present experiment were equated in terms of height, there remained significant differences in target recognizability. Thus, equating targets along the simple metric of height means that all of the information within the target height is uncontrolled. To equate targets in terms of discriminability one would be required to run extensive experiments with large subject and target populations

to obtain a set of equally recognizable targets. An experiment such as this was beyond the scope of the present effort. The only alternative would be to employ abstract figures as targets because more control could be exerted over the information content of an abstract figure as compared to a real vehicle. This procedure, however, suffers from the drawback of not providing a simulation that mimics an operational situation. Thus, the question reduces to the difficult tradeoff between better experimental control and a realistic simulation.

The learning effects found in the Martin, et. al. study were rigorously and well controlled by those workers by pretraining their subjects with the targets to a criterion of three successive sessions, of 20 target presentations per session, with less than a 10 percent improvement in recognition performance. However, the exigencies of personnel procurement and utilization as subjects in the present experiment precluded extensive pretraining to control for learning effects. However, the sessions in the present study were counterbalanced for the order of presentation of the 27 experimental conditions as well as target type as a means of partially controlling and minimizing the impact of differential learning effects.

REGRESSION EQUATIONS ACROSS GROUPS

That an analysis of variance found no differences among groups, as discussed previously, suggests an appropriate analysis is to calculate a regression equation for the entire data set; that is, by collapsing the data across groups. Furthermore, the regression equations need to be calculated in terms of the real world values of the independent variables, and not in terms of the RSM coded values, if the equations are to be useful as design guidelines. The results of this analysis are presented in Table 8 which presents both the visual angle and number of emitters data. Note that because the values of the independent variables have been transformed into real world values and are no longer in coded RSM form, the magnitude of the regression coefficient no longer is indicative of the relative importance of the terms in the regression equation. Therefore, the terms have been ordered by the proportion of variance accounted for by the terms.

TABLE 8. OVERALL REGRESSION EQUATIONS, REAL WORLD VALUES, ENGLISH UNITS

Independent Variable					
Visual Angle			Number of Emitters on Target		
Term	Coefficient	% Variance	Term	Coefficient	% Variance
Constant	56.5127	-	Constant	6.2267	-
VD	-1.4592	35.07	RR x VD	-0.0009	6.11
VD^2	0.0130	7.68	ES x EL	-0.00001	3.07
OT x RR	0.0096	1.63	OT	-0.5212	1.77
ES x EL	-0.0043	1.12	OT x EL	0.0034	1.05
OT x VD	-0.0094	0.071	RR	-0.0047	0.91
			VD	0.2005	0.76
			ES x VD	-0.0030	0.60
			VD x EL	-0.0014	0.27
			OT x RR	0.0082	0.24
Multiple R = 0.6798 R^2 = 0.4621			Multiple R = 0.3844 R^2 = 0.1477		

The terms of this regression equation are in English units, with emitter size (ES) specified in mils (0.001 in.) and on-time (OT) in milliseconds. Viewing distance (VD) is in inches, refresh-rate (RR) in Hertz and emitter luminance (EL) in foot-lamberts. The visual angle dependent variable is measured in arc min.

Table 9 presents the same equations, but with the terms specified in SI units. ES and VD are in centimeters, EL is in candela/meter^2 and visual angle is in milliradians. The units of OT and RR are milliseconds and Hertz, respectively.

As would be expected, the terms that enter these equations bear some resemblance to the regression equation calculated on individual group data. However, in view of the variability between groups as to which terms enter the equations, little benefit obtains from a detailed comparison of the present equations with the individual group equations.

TABLE 9. OVERALL REGRESSION EQUATIONS, REAL WORLD VALUES, SI UNITS

Dependent Variable					
Visual Angle			Number of Emitters on Target		
Term	Coefficient	% Variance	Term	Coefficient	% Variance
Constant	15.0509	-	Constant	6.2340	-
VD	-0.1358	35.07	RR x VD	-0.0003	6.11
VD^2	0.0006	7.65	ES x EL	-0.0008	3.07
OT x RR	0.0050	1.63	OT	-0.5221	1.76
ES x EL	-0.2769	1.12	OT x EL	0.0010	1.05
OT x VD	-0.0022	.71	RR	-0.0048	0.91
			VD	0.0789	0.76
			ES x VD	-0.4635	0.60
			VD x EL	-0.0002	0.28
			OT x RR	0.0082	0.25
Multiple R = 0.6798 R^2 = 0.4641			Multiple R = 0.3644 R^2 = 0.1477		

These equations would be useful for design purposes by entering values of the appropriate terms and multiplying by the indicated coefficients. An optimal design would be one that minimizes the predicted value of the independent variable. However, it must be stressed that these equations are only useful for the independent variables used in this study and only within the ranges herein investigated. The latter point is made because the quality of prediction is poor outside the ranges of the independent variables actually investigated (Mills and Williges, 1973; Scanlan, 1975).

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

To reiterate, the purpose of this study was to determine which variables, selected from a large set of candidate variables, strongly influence performance with matrix displays. Such data are necessary to provide information to designers concerning which variables are critical and which may be traded-off to achieve a cost-effective design. This study has shown that designers have wide latitude in selecting combinations of matrix display variables to either maximize performance or minimize cost.

The four different emitter shape-packing format combinations did not significantly influence performance. Therefore, from the design standpoint emitter shape and packing format are not critical parameters. The designer can select the shape-format combination that is most cost-effective for a particular situation. However this conclusion is, at present, applicable only to a certain class of shape-format combinations, namely those which, in the limit, can achieve 100 percent active area. It remains an empirical question whether emitter shape-packing format combinations that cannot, in the limit, achieve 100 percent active area, such as circular emitters packed in orthogonal and rhombic formats or hexagonal emitters in an orthogonal matrix, will either improve or degrade performance.

It is instructive to consider which quantitative variables were found not to influence performance. The temporal variables, on-time and refresh rate, did not appear to be major performance predictors and thus, these variables may be assigned values to achieve a cost-effective design. Furthermore, the lack of strong effects due to the temporal parameters of the display has implications for further human factors experimentation with matrix displays. Temporal variables could easily be eliminated from future experiments, simplifying both experimental designs and simulation hardware.

The conclusion that temporal factors of the display play no role in predicting performance must be tempered somewhat because of the way in which the display was refreshed. Because the matrix display simulator employed a projection technique, there was no way to manipulate independently the refresh rate and on-time of individual emitters. As a result

all emitters in the display were refreshed simultaneously. Such mass refreshing contrasts to the situation in actual working sensor matrix displays which typically employ sequential refreshing, typically on a line at a time basis. It is not clear if temporal factors of the display would exert more influence on performance with displays employing some kind of sequential refreshing. Future research ought to be directed at this question.

Another aspect of the temporal parameters of a matrix display that ought to be addressed in future studies is the problem of rise and decay times. In the present simulation the rise and fall times of each refresh field was at most 6 ms, which is very short compared to the integration time of the visual system. However, some matrix display emitter types, particularly liquid crystal elements, have rise and fall times on the order of 100 to 150 ms, which is equal to or greater than the integration time of the visual system, depending on the state of adaptation (Barlow, 1958). Such long rise and decay times might seriously influence performance, and this question requires further study.

Emitter size was also found not to strongly affect target recognition performance. In this experiment the emitter spacing was held constant, therefore, the emitter size variable may also be cast in terms of percent active area. Thus, saying that size did not influence performance is the same as saying that changes in percent active area do not influence performance. In this experiment active area ranged from 20 to 90 percent and these results confirm and extend the data of Martin, et al. (1975) demonstrating no significant impact on performance when percent active area was varied between 55 and 100 percent. Thus, designers may be constrained more by cost considerations than operator limitations when considering emitter size.

Emitter luminance also did not exert a strong effect. This conclusion must be tempered by the fact that it applies only to the range (1.9 to 60 fL) investigated here. This range corresponds to the low to mid photopic levels of human light adaptation (Graham, 1965) and it remains an open question whether the same conclusion would apply to displays operating in the scotopic or high photopic ranges. In order to specify an optimal luminance, careful consideration must be given to the environment in which the display is intended to be used.

Viewing distance, however, was shown to be an important variable. Because the actual viewing distance from a display will rarely, if ever, be a variable that can assume a wide range of values in a design situation, it is more informative to determine how changes in viewing distance influence the subtense of the emitter spacing. The results show that performance is optimal when emitter spacing is about 0.42 mrad (1.46 arc min). The actual value of the emitter spacing in centimeters or inches depends, of course, on the intended viewing distance and is given by the relation $ESp = 2VD \tan \frac{\theta}{2}$, where ESp is emitter spacing, VD is viewing distance and θ is the optimal visual angle. With emitter spacing thus fixed, the emitter size can be selected so that the percent active area is between 20 and 100 percent, which is the range of active area where performance levels are comparable.

The reader may question why the above discussion was directed at setting an optimal emitter spacing rather than an optimal emitter size. That is, the optimal value of 0.42 mrad (1.46 arc min) could also specify an optimal emitter size. The reason is that determining an optimal emitter spacing yields a display that maximizes the number of emitters across a target. A numerical example will clarify this point. Suppose we wish to construct a display with square emitters in an orthogonal matrix with 80 percent active area which is to be viewed at 75 cm (30 in). The relation given in the preceding paragraph can be used to find either the optimal emitter spacing or the optimal emitter size by substituting into the equation the viewing distance and optimal visual angle of 0.42 mrad (1.46 cm min) for θ. If the equation is solved for emitter spacing then emitter size must be constrained to give a display with 80 percent active area. Conversely if the relation is solved for emitter size, then emitter spacing must be constrained to give a display with 80 percent active area. Solving the above equation yields a figure of 0.032 cm (0.0127 in). Again, this figure could specify either emitter spacing or emitter size. If it is taken to specify emitter spacing then emitter size would be found by the equation (Emitter size^2/emitter spacing^2) x 100 = percent active area. Thus with a spacing of 0.032 cm (0.0127 in) the emitter size, for a display with 80 percent active area, is 0.0289 cm (0.0114 in). On the other hand, if emitter size is set at 0.032 cm

(0.0127 in) by the equation given in the preceding paragraph, then the emitter spacing works out to be 0.036 cm (0.142 in). Thus it can be seen that optimizing emitter spacing, rather than emitter size, yields a display with slightly more emitters across a target.

In making recommendations for future research, it is perhaps of greatest importance to develop an improved matrix display simulation. The single advantage of the present photo-optical simulation was the ability to provide moving targets. However, the drawbacks to this simulation outweigh this advantage. First, matrix mask simulation is difficult and somewhat inflexible. In the current simulation, masks were generated on a computerized plotter and while good masks can be fabricated to precise specifications with this system, any changes in the matrix specifications require the generation of a new mask, thus reducing flexibility.

Second, the technique of optical projection through a mask provides only a first approximation to a true matrix display. That is, information in the imagery located behind the inactive area of the mask is lost. This is another way of saying that here is no control of the sensor-to-display mapping characteristics. This is a potentially important variable with matrix displays which ought to be investigated by human factors experimentation, but which cannot with the current simulation.

Third, projecting photographic imagery through a mask allows the possibility of modulation within a matrix element. A fundamental feature of a matrix display is no intra-element modulation. This problem was ameliorated in the present simulation by defocusing the imagery to eliminate intra-element modulation, a method with obvious drawbacks.

A proposed alternative simulation would use a combination of film and computerized image processing in the following manner. An original high-resolution image would be digitized. To simulate the sensor to display chain three transformations of the digitized image are required before the digitized image is transferred to film. First a transformation is accomplished to simulate sensor characteristics. This potentially important variable in sensor displays could then be experimentally manipulated and various values of sensor resolution as well as discrete versus continuous sensor types could be simulated.

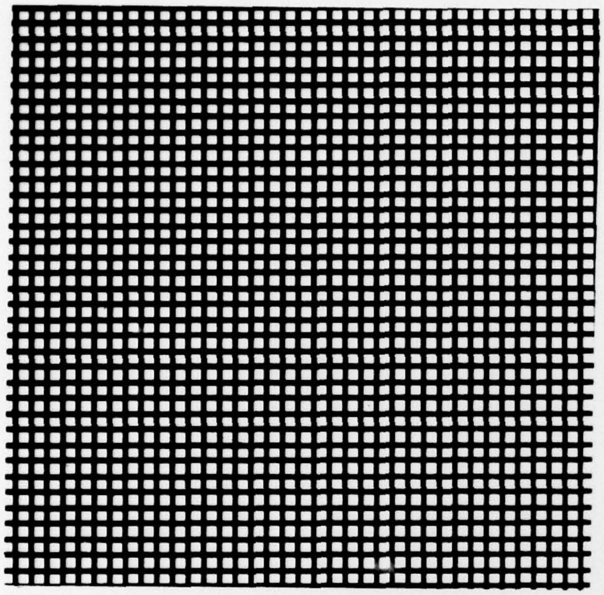
The second transformation applied to the digitized image would simulate the sensor to display interface. In this way, simulation of sensors perfectly matched to the display could be achieved in addition to situations where varying degrees of sensor-display mismatch occur. At present these variables cannot be experimentally manipulated.

The final transformation would simulate the matrix display. This transformation is, of course, the essence of a matrix display simulation and achieving it through computer control would allow enough flexibility to accurately simulate either existing or proposed matrix displays.

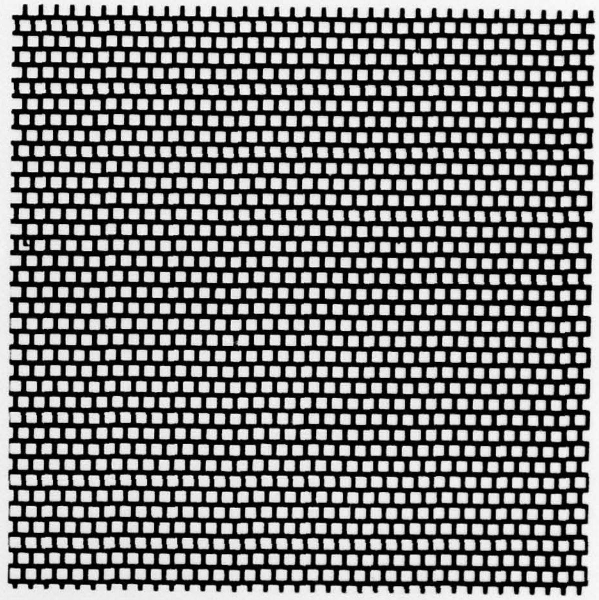
Another advantage of this technique is that targets could be embedded in realistic scenes, further enhancing the accuracy of the simulation. This technique can result in more realistic target embedding as compared to optical-photographic processes because the problem of detectable edges on the embedded target is largely removed. Thus the very important question of how design parameters of matrix displays influence detection and/or recognition of targets in realistic backgrounds can be addressed.

APPENDIX A

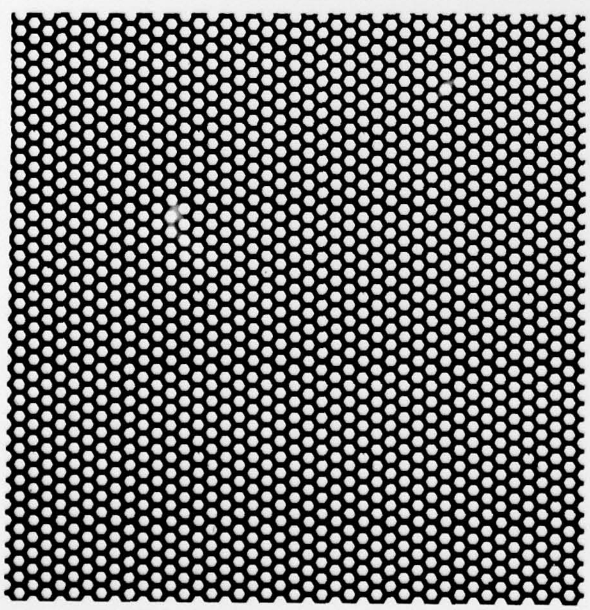
EXAMPLES OF MATRIX MASKS



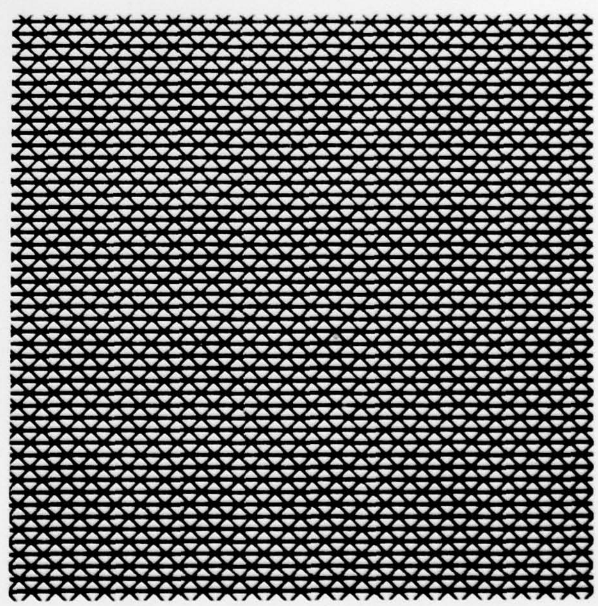
Square emitters orthogonal packing



Square emitters non-orthogonal packing



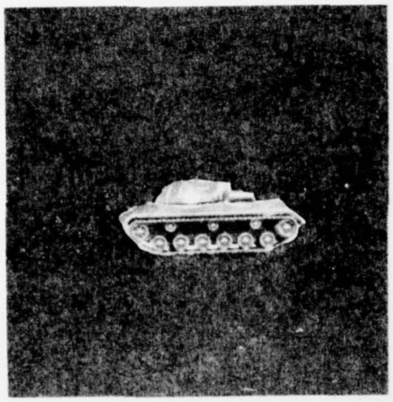
Hexagonal emitters rhombic packing



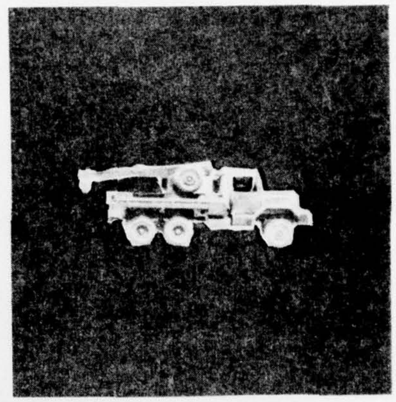
Triangular emitters orthogonal packing

APPENDIX B

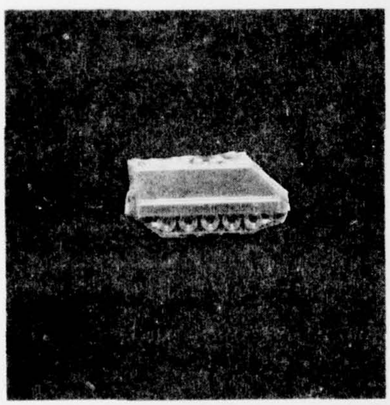
TARGET IMAGERY



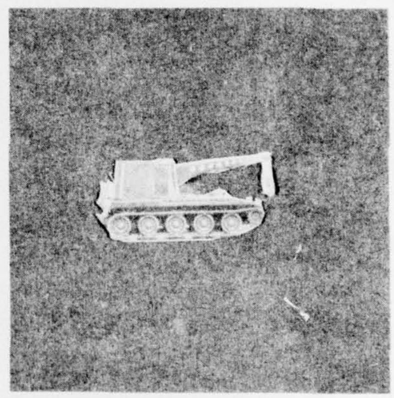
Tank



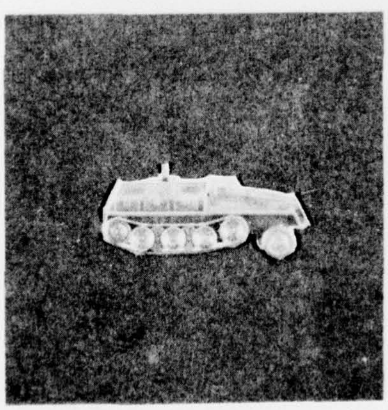
Tow truck



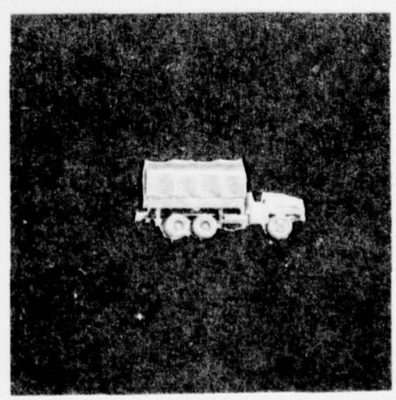
APC



Crane



Half track



5-ton truck

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